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Review of windcatcher technologies

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ABSTRACT

Mechanical cooling systems in buildings are the main producers of carbon dioxide emissions, which have negative impacts on environment and amplify global warming, particularly in hot climate. Due to the lack of energy supply, windcatchers can be utilized as a sustainable attempt for cooling and ventilation purposes. The objective of this paper is to review and provide a comprehensive literature on windcatcher system for space cooling and ventilation. The concepts were discussed according to the relevant parameters of windcatcher, i.e. windcatcher attributes, windcatcher configurations and windcatcher technologies. The pros and cons of this green architectural feature have also been highlighted and the future research need in this realm of study is proposed.

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1. Introduction

Depletion of natural resources, global warming and increase of fossil-fuel price is a real concern of human beings [1]. Moreover, the population growth has caused more than 200% increase of CO_2 emission from 1995 to 2011 (see Fig. 1). Buildings sector account for more than 40% of the total world's energy consumption [2]. The fact is that energy used in our buildings, including ventilation, heating, and cooling systems accounts for more than 60% of total buildings energy consumption [3]. Therefore, natural ventilation increasingly gained the attention of building stakeholders to reduce

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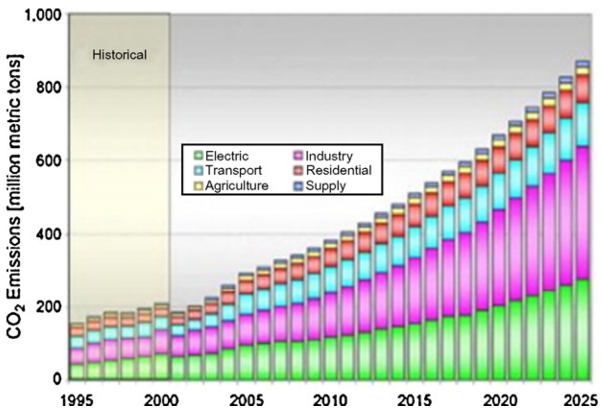

Fig. 1. CO_2 emission from 1997 to 2025 [10].

energy consumption and has opened a new area of study known as low energy architecture [4,5].

Wind as a free driving force is one of the important renewable energy [6]. This green energy, not only provides a good indoor environmental quality but also provides a comfortable, healthy and hygiene indoor climate. Wind related green architectural features, i.e. windcatcher, solar chimney, light well as well as atria are influential in increasing the stack effect as a ventilation driving forces [3,7–9].

One of the natural ventilation devices, neglected in current building industry, is the windcatcher or wind tower system. The concept of windcatcher has been commercially applied in the Britain for the past 30 years [11]. Despite the fact that utilization of the passive system is very important for combating the current challenges of the world, windcatcher is drastically ignored in designing new modern buildings [7,12,13]. Moreover, many scholars and academicians did not propose employing windcatcher in the extreme hot and humid climate such as tropical climate since they believed that the buoyancy effect is the main driving force of windcatcher which in tropical climate is not significant.

That stereotype motion has resulted not to conduct enough research on utilization of windcatcher in extreme hot and humid climate. Due to the lack of windcatcher research done in hot and humid climatic conditions, this paper takes an opportunity to include measurement results of a windcatcher research under hot and humid climatic conditions by the authors.

2. Windcatcher attributes

Windcatcher is an architectural feature mounted on the roof of a building which looks like a tower and brings in the fresh air from outside [14]. Windcatchers can be categorized in three following groups namely: vernacular windcatchers, modern or commercial windcatchers and super modern windcatchers. The foundation of these three types of windcatchers is almost the same. However, for the advancement of technology, increase the price of energy and land, and change in the expectation of people some changes have been made to the vernacular windcatchers to make it useable for the present situation.

Windcatcher has been utilized in the hot and arid regions, particularly in the Persian Gulf region, i.e. Iran, Iraq, Dubai, Qatar, and other Arab countries in one hand and north of Africa region, i.e. Algeria, Egypt and other north African countries in another hand [12]. This passive tool has been the main cooling system of these regions for the past three thousand years, functioning to reduce the building heat load [7,12,15–20].

The function of this technology is not very complicated. Based on the observation of authors, there are various forms of

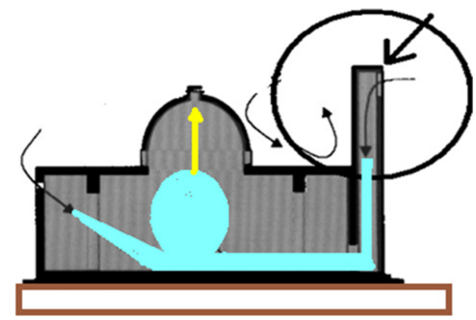

Fig. 2. Arabic windcatcher or Malqaf [27].

windcatchers in terms of height of tower, windcatcher cross-section, and the number of openings, which is related to building structure as well as the architect who has designed it.

Despite all the advantages of windcatcher, some academicians have argued on the utilization of windcatcher, because it is a place that insects and dust may enter easily [21]. This problem is more conspicuous in South-East Asia and Africa where Dengue and Malaria fever kill thousands of people each year. Another weakness of windcatcher is that the control of the volumetric flow rate is almost zero [21]. Likewise, the windcatcher is not very efficient for the areas with low wind speed [21]. In this part, the importance of different factors that contribute in windcatcher operation and different type of windcatcher will be highlighted.

2.1. Vernacular windcatcher

Vernacular windcatcher is a type of green technology, which is called Baud-Geer in the Persian Gulf area and Malqaf in the Arabic architecture such as Egyptian architecture [22–24]. Malqaf is regarded as a bidirectional windcatcher which is mounted on the top of Arab's covered court yard [25] (Fig. 2). Malqaf is normally combined with another architectural element known as Salasabil which is a wavy marble plate that is linked to a source of water [25]. Muhib Din Al Muwaqqi house in Cairo can be regarded as a popular example of this kind of windcatcher [26].

Baud-Geer, on the other hand, is not only bidirectional and has diverse forms, and various shapes and they are used during summers and are closed during winters [28]. This element height is normally ranged between 5 and 34 m [29]. Based on an archival study of authors and their field observation, the tallest vernacular windcatcher of the world is 33.80 m located in Dolatabad garden in the city of Yazd. In the Persian Gulf vernacular architecture, the design of the form and shape of this technology depended on the dignity, richness and social position of the building owners [30]. Besides, an increase of the height in a windcatcher enables it to capture the faster winds with less dust [7,21,30].

These traditional windcatchers are normally divided into four quadrants. This makes the windcatcher system safer to periodic wind changes [16]. There are also various architectural forms of windcatcher with diverse efficiency (see Fig. 3).

2.2. Modern windcatcher

There has been an increasing awareness of the application of windcatcher in the world which triggered to use the concept of windcatcher, including modern technology and current concerns. This awareness led to the invention of many new modern and commercial windcatchers. For instance, University of Qatar in Doha incorporated a brand new type of simple windcatcher, which was completely different with the existing vernacular windcatchers (see Fig. 4).

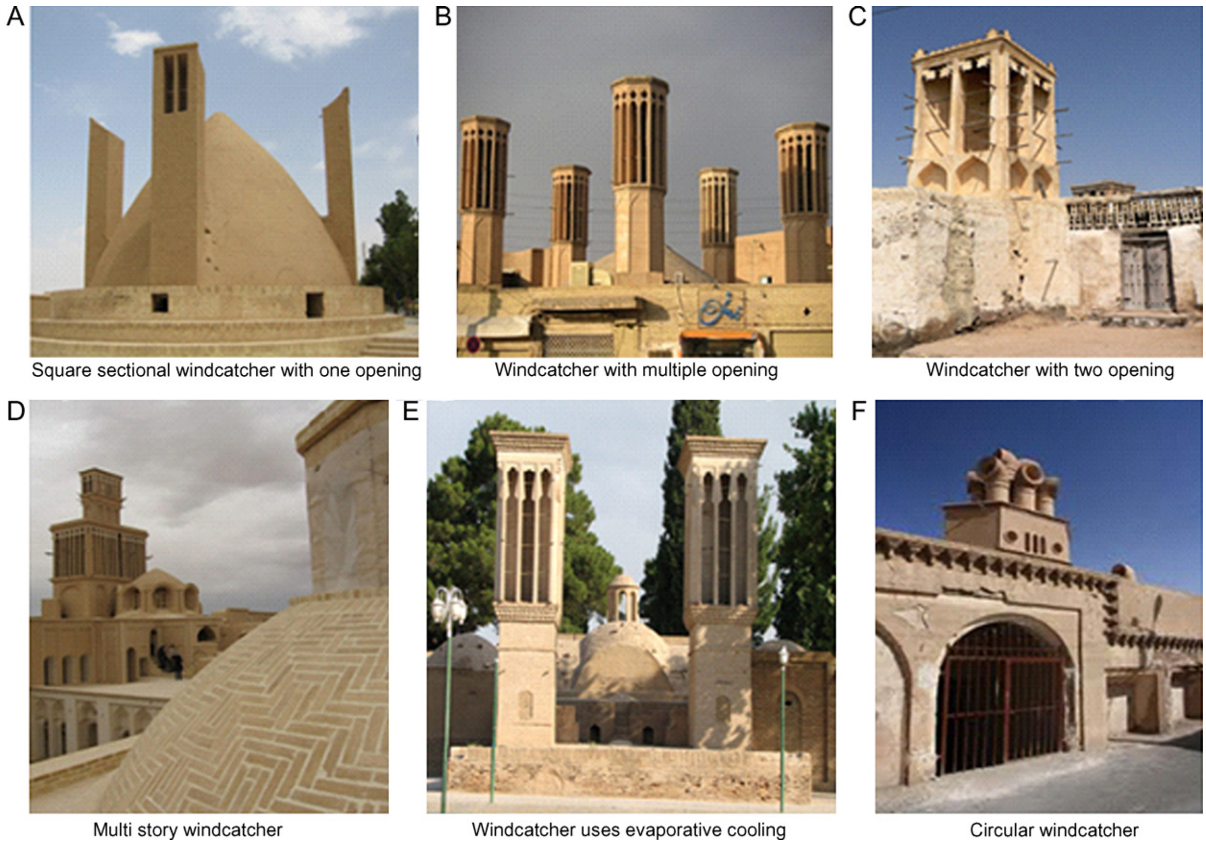

Fig. 3. Different forms of vernacular windcatchers.

Fig. 4. New type of windcatcher used in University of Qatar Doha [25].

Advancement of new technology has given the building stakeholder more opportunities to access to controlling options on different building components. For instance, a newborn type of windcatcher which posses dampers, various types of sensors and adjustable ceiling ventilator known as Monodraught has been introduced to building industry. Monodraught windcatchers are normally automatic and the mechanism allows the temperature, humidity, air flow, noise level, and CO_2 to be adjustable depending upon the need of the space [17,25]. Some of this new commercial windcatchers incorporates both natural ventilation and natural lighting and in an integrated, energy-free system (see Fig. 5) [31].

2.3. Super modern windcatcher

Combining the concept of green life and accessibility to high-tech instruments enabled the architects of the new millennium to transcend the conventional boarders. The "Wind Catcher Tower concept, "a suggested 125 floors tower which is designed for future is an example of above statement. The form of this tower designed in an aerodynamic form and can absorb the wind power and use it to produce electricity [33]. The proposed design foundation is on a rotating plate which enable the tower to orbit and move into the right position, where can catch wind and lead the wind to the top to activate three wind-generators and produce electricity for cooling, ventilation and other consumptions (see Fig. 6) [33].

Another example of super modern windcatcher is Dubai's Burj al-Taqa or the Zero-Energy Tower in the Desert. This 322 m tall tower is equipped with a 60 m turbine installed on its roof which, partially caters for the needs of tower electricity [34]. The rests of the needs of this tower are provided using solar energy as well as hydrogen fuel, which is supplied by catalyzing the sea water [34].

The idea of utilizing windcatcher in building has not been confined to only the Middle East. There are numerous super modern windcatchers installed in various buildings internationally such as Council House 2 (CH2) in Melbourne Australia, which saves up to 80% of energy needs [35] (see Fig. 7).

The technology behind this windcatchers is more sophisticated where five windcatchers are installed in the southern facade of this building, connecting to three large tanks in the basement [35]. Large tanks are filled up with 10,000 phase change material balls, which freeze at 15° C. This frozen balls can cool down the circulating water of coolers through convection [35].

2.4. Windcatcher with different opening

The number of opening is an important parameter in designing a windcatcher. Generally, windcatchers are categorized in two groups of unidirectional and bidirectional [36]. The former takes the wind from the top inside and then the air is allowed to exit

Fig. 5. Sample of Modern commercial Monodraught [32].

Fig. 6. “Wind Catcher Tower” is a proposed design for future [33].

from another part of building, and the latter takes the wind from its top, let it travel across the building and then up again through the lee side of windcatcher [36].

The bidirectional windcatchers are normally divided into their vertical axis. Ghaemmaghami and his colleague have reported four types of windcatcher based on their opening namely: one directional, two directional, four directional and eight directional windcatchers (see Fig. 8).

Montazeri and his colleagues based in Yazd city, known as city of windcatchers, conducted a study to investigate the number of opening of windcatcher and its efficiency [29,37]. The study presented that height, cross section and place of windcatchers as well as the numbers of opening are the rubrics that contribute in windcatcher efficiency [37]. They further, utilized experimental wind tunnel and smoke visualization test as well as CFD simulation to examine the efficiently of windcatchers with various numbers of opening.

Fig. 7. Windcatchers used in Council House 2 in Australia [35].

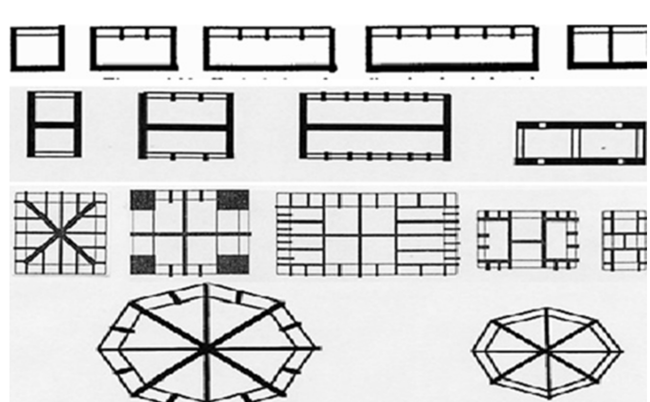

Fig. 8. Cross sectional of vernacular windcatchers [18].

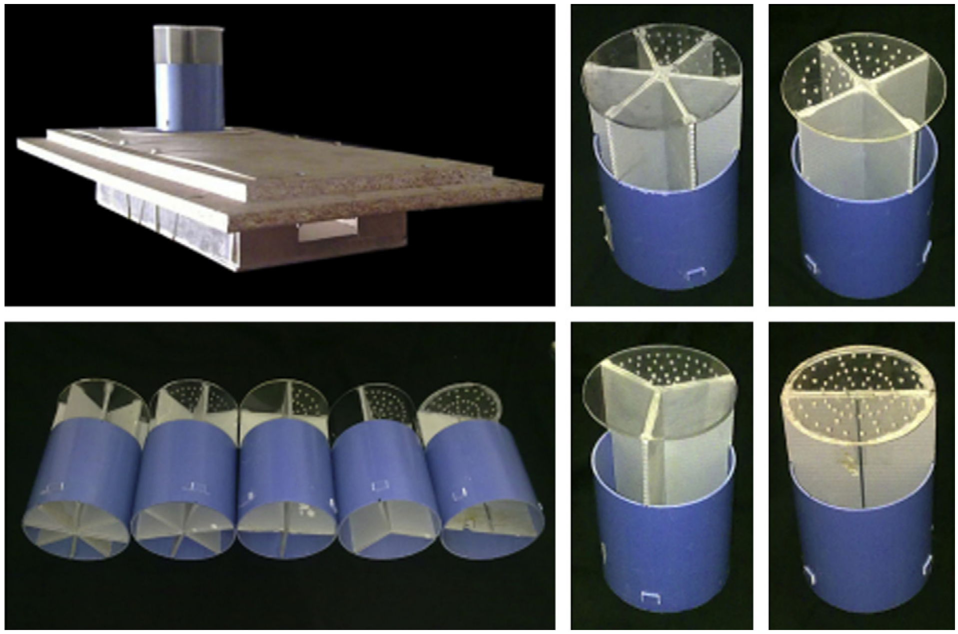

Fig. 9. Windcatcher models with different opening [29].

The objective of their study was to observe the hydrodynamic behavior of multi and single opening windcatchers. Therefore, they made five following cylindrical models: two, three, four, six and twelve-sided windcatcher (see Fig. 9). In conducting the wind tunnel and smoke visualization test, the air flow rate through each opening needed to be measured to gauge the net induced air flow rate by each of the windcatchers. Accordingly, some stainless steel static tubes and sensitive tiny pitot were employed to measure the different channel's air flow rate [29].

The wind tunnel and smoke visualization tests were conducted in the uniform flow wind tunnel in the following three various wind velocities of 10, 15 and 20 m/s at different wind angles of 0–45° in 2.5 increments [29].

Because of separated flow phenomenon, and existence of a circulation zone of the incoming air stream which occurs at the entrance openings and near the lower edge of the model, which causes a non-uniform flow inside of the windward openings several pitot and static tubes needed to be employed. Hence, the following formula was used:

$$Q = \sum_{i=1}^{n} Ai\, vi \quad (1)$$

In this formula, the flow rate passing the channel of the windcatcher is called Q and Ai is the area of the portion i and vi are the velocity of portion i respectively. Table 1 presents the details of pitot and static tubes used at the upper and lower surfaces and wind angles of Montazeri study.

Referring to Table 2, the result shows that adding the number of opening in windcatcher decreases the efficiency [37]. There is a relationship between the wind angle and the induced air flow inside the windcatcher. For instance, a two-sided windcatcher has the highest air flow at zero wind angle [37]. Despite the above fact, the effect of wind angle will decrease if the numbers of opening increase [37]. The study also showed that a rectangular device catch a higher induced air flow for both one and two-sided systems [37].

Table 2
Relationship of windcatcher with different opening and airflow.

WindcatcherType	Wind angleDegree	Rate of net air flow (m^3/s)	
		Experiment	CFD
Two opening	0	0.029	0.031
Two opening	15	0.028	0.029
Two opening	30	0.17	0.019
Two opening	45	0.022	0.023
Two opening	60	0.014	0.016
Two opening	75	0.015	0.017
Two opening	90	0.015	0.017
Three opening	0	0.026	0.030
Three opening	15	0.026	0.029
Three opening	30	0.025	0.026
Three opening	45	0.017	0.018
Three opening	60	0.016	0.019
Four opening	0	0.024	0.029
Four opening	15	0.018	0.026
Four opening	30	0.018	0.028
Four opening	45	0.027	0.029
Six opening	0	0.021	0.024
Six opening	15	0.027	0.029
Six opening	30	0.028	0.029
Twelve opening	0	0.025	0.026
Twelve opening	15	0.027	0.027

Table 1
Details of angle and Pitot tube used in the study of Montazeri.

Windcatcher model	Pitot tube Up	Pitot tube Down	Static tube Up	Static tube Down	Wind direction Degree
Two opening	28	28	8	8	0–90
Three opening	22	22	6	6	0–60
Four opening	14	14	4	4	0–45
Six opening	11	11	3	3	0–30
Twelve opening	7	7	2	2	0–15

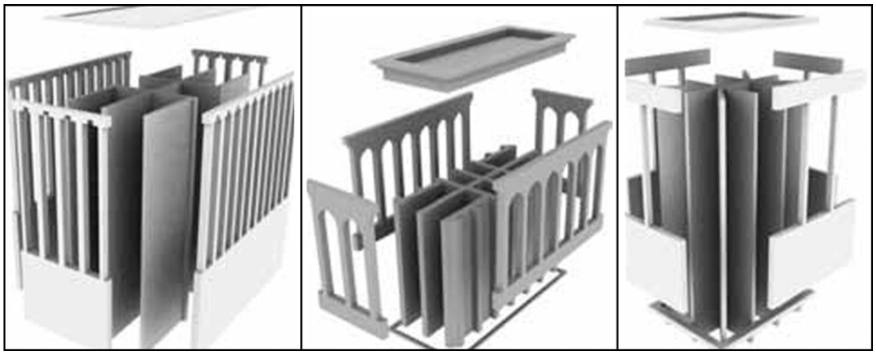

Fig. 10. Different components of a normal windcatcher [38].

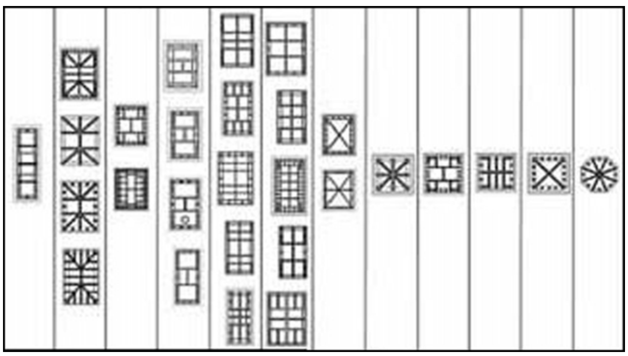

Fig. 11. Various plan cross sectional windcatcher [38].

The study also concluded that although increasing the number of openings reduces the rate of induced wind and ventilation, it makes the windcatcher less sensitive over different inclination angel [37]. In other words for the places which there are no prevailing wind direction, it might be considered more suitable.

2.5. Shape of windcatcher

In vernacular architecture, windcatchers had the square, rectangular and octagonal cross-section where the most prevalent shape is reported to be the square type [18]. One component of a windcatcher is its partition, which divides the main tower to various shafts [18]. There are two types of partition namely; main and secondary partitions where the former, starts from 1.5 to 2.5 m above the ground floor level, continue to the top of the windcatcher and the latter remain as wide as the external wall, about 20–25 cm wide. The role of partition is not only to divide the windcatcher to smaller shafts and increase the air motion cause of buoyancy effect but also to satisfy the structural needs of windcatcher (see Fig. 10).

Mahmoodi and her colleagues have reported three main forms of windcatchers, which have 28 various cross sectional plan [38] (see Fig. 11).

Even though circular windcatchers looks to be more aerodynamic and therefore, to be more efficient, based on Elmualim and his colleague's experimental investigations as well as his computational fluid dynamics (CFD) simulations the result turns out to be different [39]. They found out that the performance of four-sided square windcatcher is much higher than the circular one [39]. The reason is that sharp edges of the square windcatcher produce a big region of flow separation [39]. This flow separation imposes a higher pressure difference across the device and makes it more efficient. The above statement is in agreement with Montazeri finding for a zero angle wind direction, where a one-sided windcatcher induces air into the building almost four times more than the two-sided circular windcatcher [37].

Likewise, Liu and Mak used CFD modeling simulation to investigate the efficiency of a 500 mm square cross-sectional windcatcher. Their finding also confirmed the mentioned result of Elmualim and Awbi [16]. With regard of the form of windcatcher, Asfour et al. carried out a CFD simulation test on an integrated windcatcher with curved roof to compare the result with the normal roof. Their study represented that the integrated windcatcher with curved roof increases the air flow distribution and improves the internal air distribution [40].

Another study conducted at Eindhoven university on the venture-shaped roof employing wind tunnel experiments and CFD simulation using steady RANS and the RNG k-3 model to analyze the flow conditions, focusing on the under pressure force in the narrowest roof section [41]. This under pressure force is one of the main driving forces of passive ventilation in buildings [42]. The study, also, aimed to assess the magnitude of the under pressures generated with different design configurations of the venture-shaped roof [41]. Four following venture-shaped roof configurations were set: 1-without guiding vanes, 2- with guiding vanes at every 90 intervals, 3-with guiding vanes at every 10 intervals and 4-normal roof (see Fig. 12).

Their study revealed that style of without guiding vanes outperforms the other styles [41]. This outperforming is in terms of the magnitude of the under pressure force in the roof contraction. This phenomenon stems from the fact that adding guiding vanes increases the flow resistance. This flow resistance makes a larger part of the approaching wind flow not to pass through it and circulate, which is called wind-blocking effect [41]. The wind-blocking effect causes the venture-shaped roof with guiding vanes performs worse than the configuration without venture shaped roof.

2.6. Windcatcher with damper and egg crate grille

Dampers and egg crate grilles are some devices that are used in some windcatchers that assist the movement of large air flow rate to replenish of fresh air. Elmualim a scholar of the University of Reading in the UK employed a smoke visualization testing in wind tunnel on a four-square sections windcatcher (0.50 m × 0.50 m × 1.5 m) and CFD simulation to examine the effects of egg crate grill, damper and heat source on windcatchers efficiency (see Fig. 13). Three alternatives were studied under nominal wind speeds of 0, 0.5, 1, 2, 3, 4, 5 and 6 m/s at one direction combining the heat source and damper egg crate which its details could be found in Table 3.

In doing this study, a pitot-static tube was employed to measure the total pressures. The study team also fixed internal and external pressure taps to the windcatcher model both in the leeward and the windward side to measure static and stagnation pressures.

The study result revealed that use of the damper and egg crate grille with the damper in fully open position decrease the

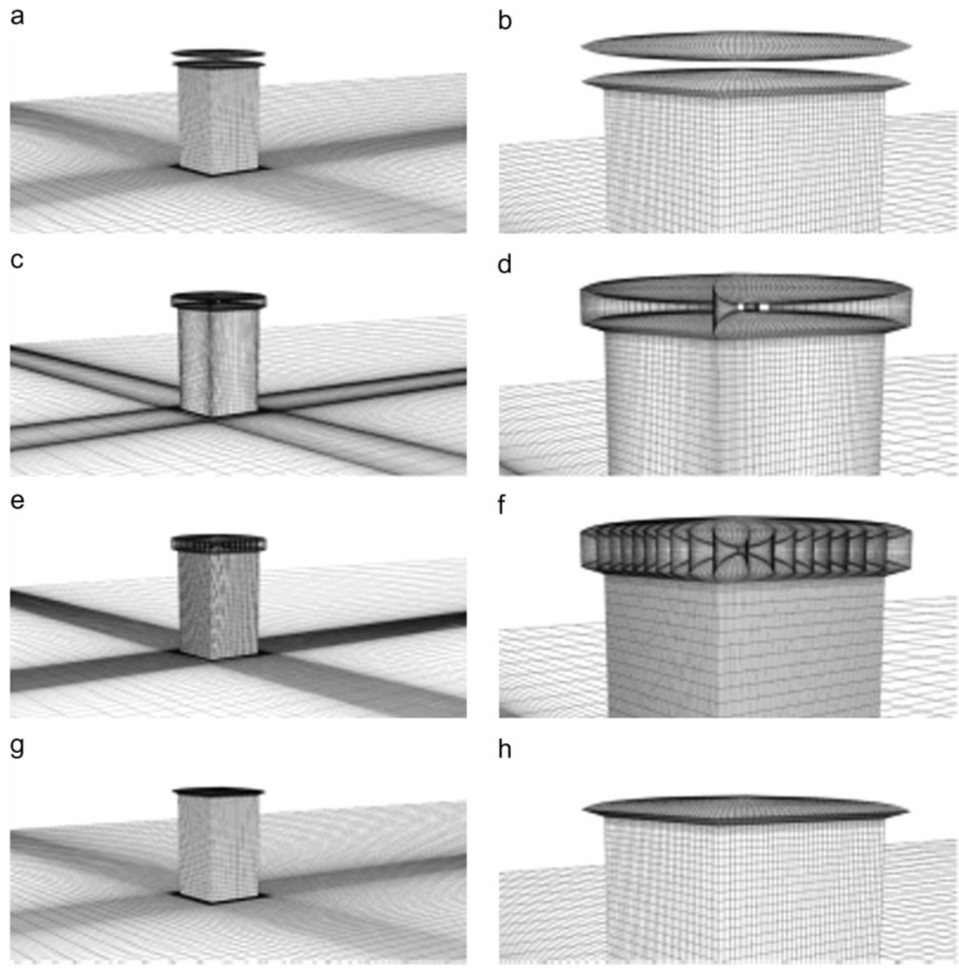

Fig. 12. Different configurations and the reference configuration: (a and b) no guiding vanes (c and d) guiding vanes every 90°; (e and f) guiding vanes every 10°; (g and h) no venturi-shaped roof [41].

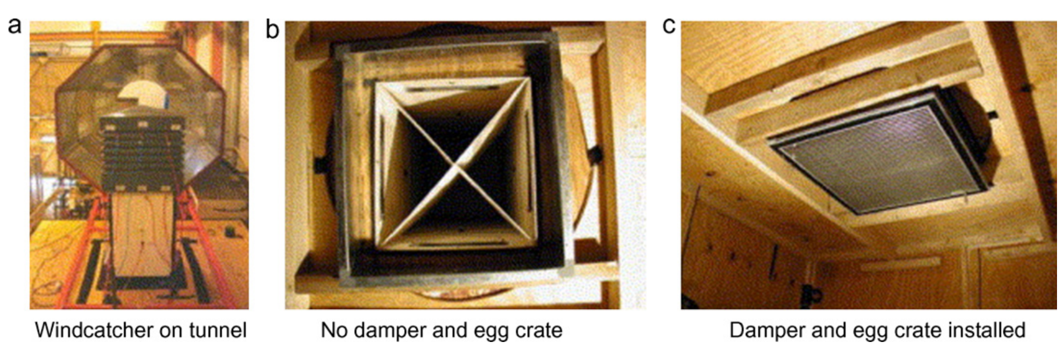

Fig. 13. Experimental device of Elmualim [15].

ventilation. The reduction of ventilation depends on the wind speed which reaches to approximately 50% when wind blows 1 m/s and 20% when wind blows 3 m/s respectively.

Likewise, damper and egg crate grille installation decreases the induced wind flow to 71% of normal configuration at an external wind speed of 3 m/s and 67% of normal configuration at an external wind speed of 1 m/s [15]. Finally, the installation of the above device decreases the windcatcher volumetric air flow with an average pressure loss coefficient of 0.10 [15].

Table 3
Details of various setting.

Case number	Wind direction α°	Wind speed (m/s)	Damper egg crate	Heat source
1	$\alpha^\circ = 0^\circ$	0–6	Does not exist	Does not exist
2	$\alpha^\circ = 0^\circ$	0–6	Damper is completely open	Does not exist
3	$\alpha^\circ = 0^\circ$	0–6	Damper is completely open	3 kW heater

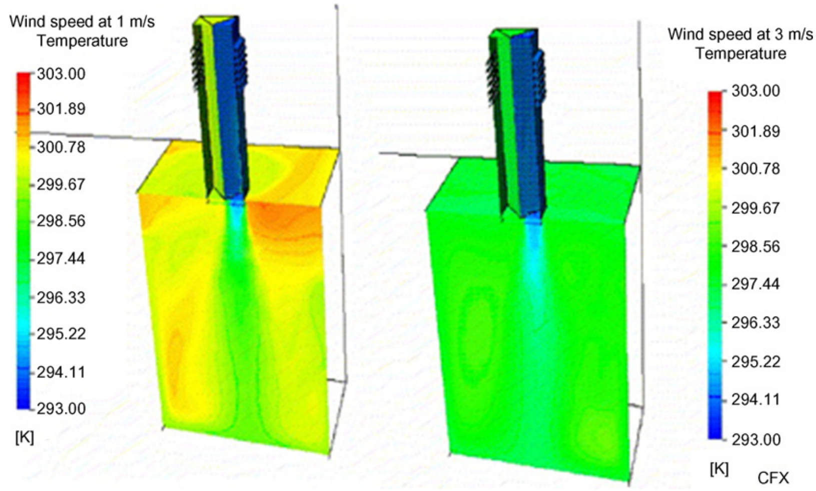

Fig. 14. Temperature effects and wind speeds of 1 and 3 m/s [15].

Another study which was conducted in Hong Kong, simulating an integrated building and a window positioned in lee ward side, indicated that in order to combat particle concentrations and streaming the distribution of airflow, which is not uniform, a damper or egg crated grill should be installed, particularly for the areas which have strong wind [7].

3. Windcatcher technology

In spite of that the utilization of windcatchers is ignored in modern architecture, advancement of technology has affected this negligent positively in recent years. A prove of this claim is the use of many modern windcatcher elements in the UK itself, where the Inland Revenue building in Nottingham, the Queen's building at Demon fort University and many other buildings employed this system to reduce their energy [15]. Operation of a windcatcher depends on some climatologic parameters such as the time of operation, i.e. day or night time, the availability of wind, and the type of windcatcher system, i.e. hybrid or normal [43].

There are two main forces of wind and buoyancy, which its effects maintain natural ventilation in this green architectural feature [44]. This technology captures the external wind and induces it into the building. This induced wind increases the both convective and evaporative inside heat [44]. It cools the inner part indirectly by removing the stored heat inside the building structure. Kolokotroni et al. carried out a study aiming to determine the driving forces and influential parameters behind this system. Their results showed that windcatcher efficiency is altered by changing outdoor wind speed, changing temperature difference and changing the location and number of openings, like windows [45].

3.1. Wind and buoyancy effects

Windcatchers are generally dependent on wind to operate. However, whether windcatchers are functional under slow wind or need fast wind to operate has always been a matter of question. For answering this question Yaghubi and his colleagues carried out a study on three naturally ventilated public buildings with different wind speed in Yazd. They learnt that windcatchers are functional in all of those places even in low speed wind locations [23]. Measuring temperature, relative humidity and airflow velocity, the research team found out even in a calm weather, windcatcher can bring thermal comfort for dwellings by inducing certain volume of air circulation [23].

Kirk and Kolokotroni conducted an experimental test using air exchange rate tests and tracer-gas decay method in three various buildings, all of which equipped with windcatcher. Their study revealed that air exchange rates are directly related to speed of the wind [46].

Extensive investigations and several researches using the CFD and full scale experimental tests have been conducted on different types of windcatchers to determine the driving forces behind its operation. In fact, windcatchers need a driving force to operate where the first force is buoyancy effect, which is due to the temperature difference [44]. This force is an upward force exerted on an immersed particle [47]. The second force is external wind [44].

There has been a dispute between scholars on significance of these two forces whereby some researchers were emphasizing on the former force as the main medium of passive ventilation, and some others on latter one. For instance, Bardan, an academician from Jordan, has proposed buoyancy effect and the difference in density of air between the inside and outside of the windcatcher as the main force of passives ventilation in windcatcher structures [48].

Meanwhile Kirk and Kolokotroni have proposed the effect of these two forces as equal [46]. However, Johns and Kribly conducted another study resulted to the fact that buoyancy is significant only at relatively slow wind [11]. Likewise, Hughes and Ming employed CFD simulation to examine the relationship between the above two forces and the indoor ventilation rate [22,44]. They found out that the external wind provides 76% more internal ventilation than buoyancy force [44]. In addition, they realized that the effect of buoyancy is negligible once there is no external induced airflow.

Their study proposed that installing a window which could provide additional external wind could increase the indoor ventilation by 47% in comparison to the time of relying solely on buoyancy force [44]. Their study proved that the optimum velocity occurs once there is a window to amplify wind effect and there is a heat source to amplify buoyancy effect (see Fig. 14).

Another study conducted in University of Nottingham in the UK on a commercial windcatcher known as Monodraught ABS550 utilizing the both measurement system uses a cone flow meter and a blower fan as well as CFD simulation to investigate its efficiency. The result of this study showed that such a modern windcatcher can easily achieve an extract flow rate of 30 l/s to ventilate a three-bedroom house if there is an outdoor wind speed of 2 m/s [17].

The result of the said study also indicated that the effect of wind direction is less than 20%. Likewise, a temperature difference of

Fig. 15. Use of evaporative technique in Iranian Vernacular Architecture [53].

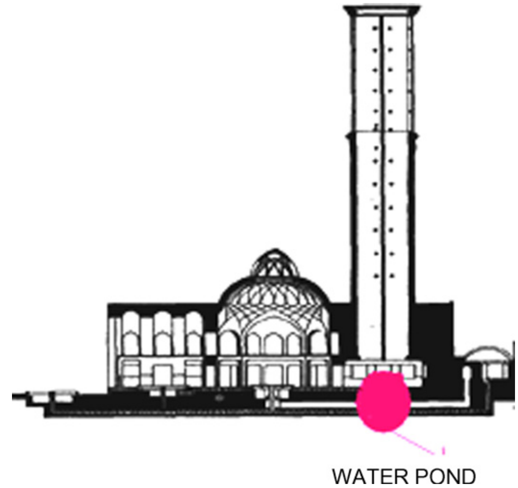

Fig. 17. Use of pond in cooling the building.

10 °C amplifies to air movement for the effect of buoyancy when the wind speed is less than 2 m/s, nonetheless, it is considered negligible when wind blows slower than 3 m/s [17]. There is a same story for a commercial wind vent whereby the fresh air is driven by the positive air pressure on windward side, exhausting air is driven by the negative pressure on the leeward side [44,49].

There also exist a secondary force namely stack effect, which is related to buoyancy [22]. This stack effect is the result of decreasing the air density for increasing the temperature [16]. Hence, the internal and external temperature difference will force the airflow to exit through the ventilator. Hughes and Ghani studied the minimum and legislative requirement of wind, employing a numerical investigation in standard passive stack device geometry and a simulated low-powered axial fan. The study revealed that a minimum of low-induced pressure of 20 Pa is required to enable the windcatcher functions properly [50].

3.2. Heat source

Installation of one heat source inside any windcatcher facilitates the movement of air flow due to buoyancy effect. Based on a study carried out by a group of scholars on the thermal comfort of residents of three buildings, it was revealed that there is a negative relationship between thermal comfort and having a too strong heat source such as strong solar radiation [23,43].

However, the result of smoke visualization and CFD simulation showed that installation of a heat source affects the performance of windcatcher in a positive way [15]. Likewise, the result indicated that installation of the heat source improves the performance of windcatcher, particularly at lower wind speeds [15].

The increase of air velocity inside the windcatcher was 54% for a wind of 1 m/s and 7% for a wind of 3 m/s respectively [15]. Moreover, the installation of heat source increased the extract flow rate by 38% at a wind speed of 1 m/s [15]. In contrast, the heat source reduced extracted flow by 2% for wind speed of 3 m/s [15]. The windcatcher with heat source was found to be able to reduce temperature by 6 °C if there would be an external and internal temperature difference of 8 °C [15].

3.3. Use of evaporative cooling

In the Persian Gulf architecture, use of water and evaporative cooling technology has been employed for centuries. For instance, use of an underground water canal known as Qanat was an integrated part of the windcatcher design (see Figs. 15 and 16). Those old-time architects were cooling down the buildings, knowing that the effect of evaporative cooling occurs once the air passes through the wet surface of the groundwater seeped inside basements [51,52]. In those designs, natural downdraft is utilized to produce the necessary airflow from the outside to the inside of the living space.

This technique was not only used in the Persian Gulf vernacular architecture, but also in Jordan and Egypt [12], where the inlet air flows were passing along a water pond or canal to cool (see Figs. 15–17). This technique employs water vapor to cool the air directly or indirectly and prevent installation of conventional mechanical cooling system which are both noisy and unsightly [55,56].

According to a study conducted by Heidarinejad and his colleagues, direct evaporative cooling is very conducive for multi climate countries such as Iran. Based on their computation

Fig. 16. Inducing air inside the water canal as a medium of evaporative technique [54].

simulation and long term meteorological measurements, this technique provides comfort conditions for more than half of the Iranian people [13]. An Egyptian scholar claims, based on an experiment conducted, evaporative cooling is the most efficient method among the entire passive cooling methods in the world [57].

This technique can also reduce the temperature up to 10 °C in arid areas [58]. Evaporative cooling has attracted many researchers such as Jiang. He and his colleague from Tokyo institute of Technology invented a type of ceramic that has a capillary force to soak water to more than one meter when the lower end of the ceramic is put inside a water pond [59]. Although, the evaporating technique is the very useful means to improve the efficiency of windcatchers, it might not be very feasible for extreme humid climate once the issues of cost and benefit are taken into the account [60].

Numerous studies have been conducted on utilization of evaporative cooling in different segment of a windcatcher. For instance, altering the height of wetted column and size of the mass exchanges located at the middle of air and windcatcher walls was suggested as a practical and efficient solution [12]. Likewise, in investigating the cooling effects of a fan-assisted evaporative windcatcher, it was revealed that more than (4/5) of the cooling effects is achieved at the top 2 m of the windcatcher [12]. Besides, they realized that the outlet temperature is just 3 °C higher than the ambient wet bulb temperature [12].

Although, evaporative cooling drastically cools down a building, the fact is that the above traditional evaporative cooling methods such as Qanat and pond cannot fit in the modern building easily. For this reason Bahadori and his colleagues proposed two new windcatcher designs, which can be incorporated in existing windcatcher without evaporative cooling as well as modern building [61].

Their design had three following configuration: (A) the windcatcher with wetted column (B) traditional windcatcher and (C) the windcatcher with wetted surfaces (see Fig. 18). The configuration number one was equipped with fabric curtains suspended from the top. The space between fabric curtains was 10 cm, and they were as high as windcatcher height exclusive windcatcher head. The research team had the curtains wetted by spraying water on their top. On the other hand, configuration number two was used evaporative cooling pads made from leaves of plants, which were wetted by spraying water on top of them.

Doing the full experiment in two different sites as well as computer simulation revealed that: both the configuration number one and the configuration number two are more efficient than the conventional one [61]. The study result also indicated that the configuration number 1 performs better with high wind speeds whereas configuration number two is more efficient in low wind speeds.

Kalantar conducted another study by doing the computation modeling using C++ program and experimental test, which revealed that if the walls of the wind tower is insulated, the windcatcher operates more efficiently and less water will be consumed [43].

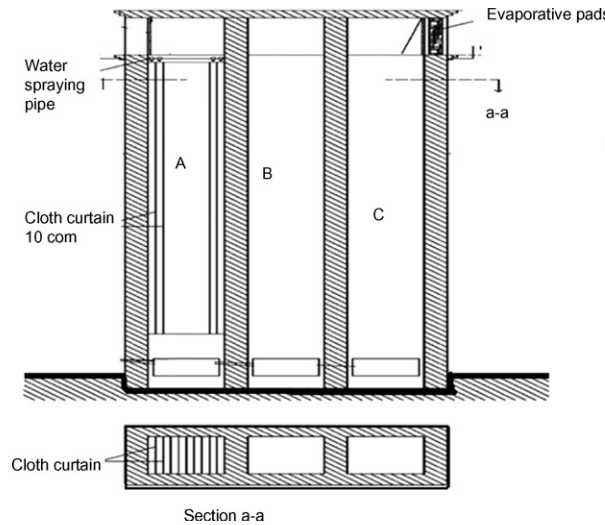

Fig. 18. The new design of windcatcher [61].

In spite of that, all the above advantage, there has always been a consensus that the evaporative cooling is not very efficient for very humid climate without dehumidification, which bears more energy consumption [3,62,63].

3.4. Hybrid commercial windcatcher system

The advancement of technology triggered a change in the use of windcatchers in combination of active heating and cooling systems. This combination is called hybrid windcatcher system which some of them requires installation of complex electrical controlling systems known as “Energy management and building automation system”(EBAS) [64] and integrated building management system (IBMS) [65].

These are electrical systems, which are literally computer-based control systems that monitor and control different cooling, heating, ventilation and other energy-related devices. An example of these hybrid windcatcher is a shopping mall called Blue-water shopping mall located near Kent city in the UK [66]. The shopping mall incorporates 39 rotating modern windcatchers, as an innovative application for passive ventilation in the UK, to ventilate the building (see Fig. 19).

The building employs IBMS connected to a weather station to operate windcatchers in conjunction with mechanical ventilation. Information about occurrence of rain, speed and wind direction, temperature and relative humidity and snow or wet fog is transmitted from weather station to IBMS.

IBMS operates the system under five phases: phase 1: under snowing, raining, and wet fog circumstances or either the average external dry bulb temperatures are outside of the range of 14–25.8 C

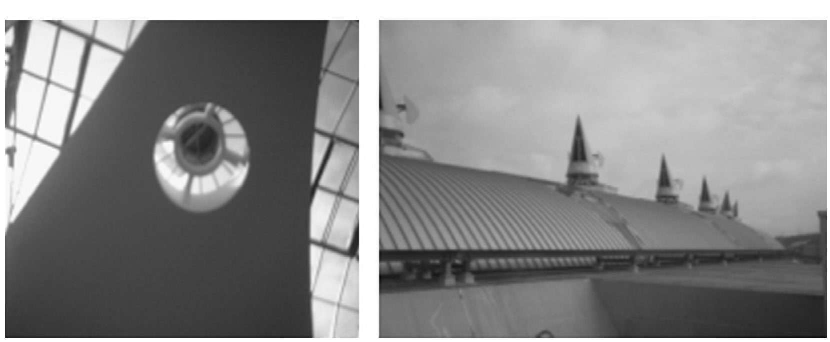

Fig. 19. Inside and outside of hybrid system [66].

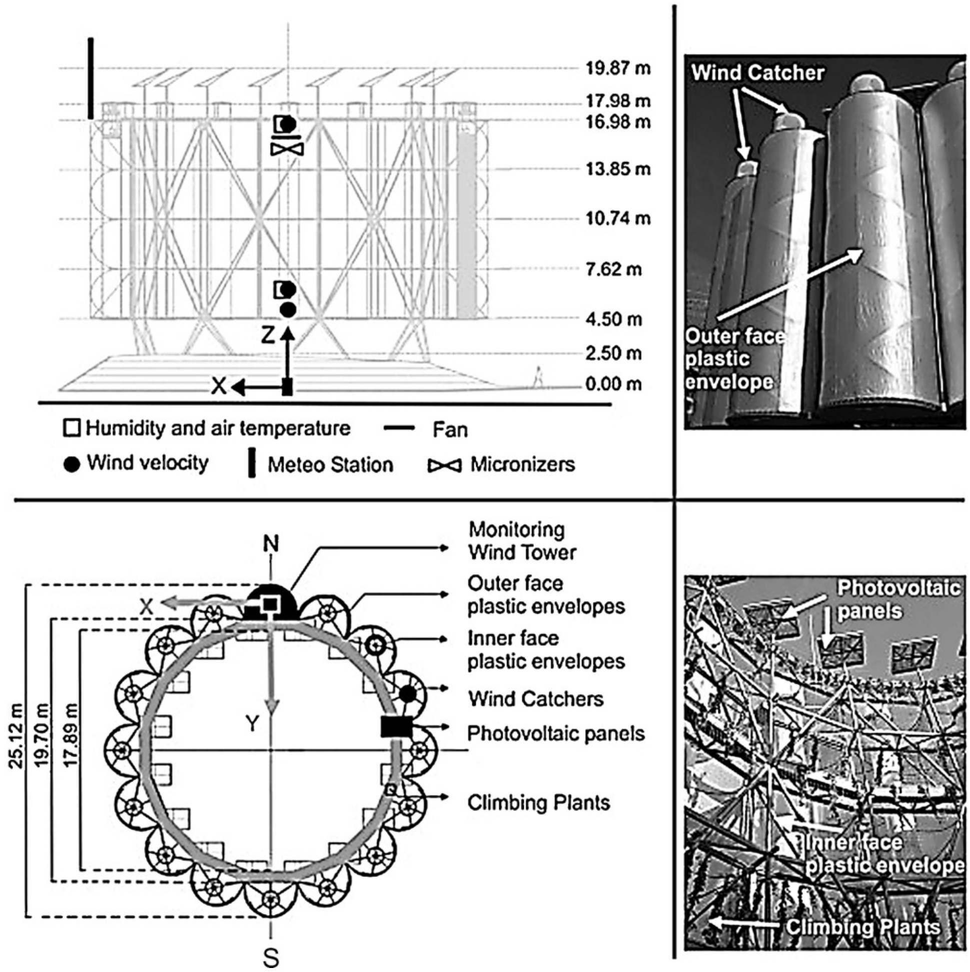

Fig. 20. Details of the project [67].

or average external wind speed is outside of the range of 1–7 m/s, the IBMS will deactivate the windcatchers and mechanical ventilation will be employed. Likewise, if average wind speed is below 1 m/s for a couple of consecutive 20 min, IBMS will run mechanical ventilation. Phase two: wind speed is between the range of 1–3 m/s, all 39 windcatchers will be utilized. Phase three: If the average external wind speed is between 3 and 7 m/s, IBMS uses only 19 of the windcatchers; and finally phase four: the sensors show that the thermal comfort indices exceeds the desired set point range, then an alarm notifies the relevant authority to use the mechanical ventilation. This system has shown an acceptable result both in summer and winter whereby based on the study of Elmualim the indoor air quality parameters were recorded within the desired range [66].

3.5. *Windcatcher for outdoor*

Conventional windcatchers is normally designed for enclosed and semi-enclosed area, nonetheless, the idea of expanding the use of windcatcher to outdoor has attracted some researchers who are experts in this realm of study. For instance, a group of scholars based on Madrid, Spain, started a project, and financially supported by European commission, to examine the use of evaporative windcatcher for outdoor urban space, i.e. a boulevard with hot and dry summer climate.

They installed sixteen windcatchers in a circular arrangement to create an activity zone for pedestrians to gauge their thermal comfort (see Fig. 20). During their data collection, the research team measured the solar radiation, temperature, wind speed and humidity. They utilized two indices of Heat index and TS index to forecast the thermal comfort.

The study result, based on sensors of wind, temperature and humidity, indicated that the windcatchers has decreased the temperate on average 3.5 °C in some places [67]. However, it was found out that the comfort level could have only been achieved in +1 m from the ground in the pedestrian zone [67]. In that position, the average saturated cooling efficiency is approximately 32% [67]. The study also proved that windcatcher not only cools down because of evaporative effect but also for the windcatchers shading effects and interestingly the effect of shading is more than the action of the evaporative systems [67].

Another example of windcatcher for outdoor is a windcatcher installed in Masdar city in Abu Dhabi to induce a convection current due to buoyancy effect (see Fig. 21). This windcatcher is equipped with some adjustable louver that can be changed based on different winds, and it aimed to be able to cool the area up to 5 °C [68]. In spite of that, no scientific report was found with regard to the performance of this windcatcher. According to the interview conducted by the users of that zone, the users were feeling thermally comfortable in 4 months of the year in the mentioned area.

3.6. *Down draft windcatcher*

As far as the technology gets more high-tech in general terms, new techniques and initiatives are also being introduced in employment of windcatcher as a cooling and ventilation medium. Down

Fig. 21. Windcatcher for outdoor -Masdar City [68].

draft windcatcher, an innovative design, is one of these new initiatives which utilizes the evaporative cooling phenomenon for vast or semi disclosed areas such as courtyards, particularly in arid regions [36,58,60,69].

This type of windcatcher, operates based on three following principals: (1) there is a positive wind presser at the entrance of the windcatcher or inlet; (2) the spray of the water at the top of windcatcher causes the air to descend since it became denser; and (3) there is a momentum transferred from the sprayed water to move the air downward [58].

The advantage of this kind of windcatchers is that it circulates the air all the time even in the absence of wind due to the buoyancy effect created by evaporative cooling [58]. A down draft windcatcher might have a different shape as well as uses various type of supplying water for evaporation but generally draws dry ambient air inside through a single inlet located at the top and cooler moist air exits at the bottom part (see Figs. 22 and 23).

Pearlmutter and his colleagues invented a new prototype of the down draft evaporative windcatcher which functions in multi stage to improve the single stage design by incorporating a secondary air inlet [58]. They aimed to make the conventional dawn draft windcatchers more efficiently in terms of water consumption. Therefore, they incorporated a secondary air intake at the middle of the device equipped with a high-tech water spraying system. This water spraying system had a very low spray drift beyond the base of the tower, to reduce maintenance costs.

The study result revealed that the proportion of second air blown through the secondary inlet is drastically substantial [58]. Likewise this system was recognized to be highly efficient in terms of conserving water and suggested as a practical passive solution for semi enclosed spaces [58]. The maximum efficiency of this system is achieved if a very fine spray is being employed. [58].

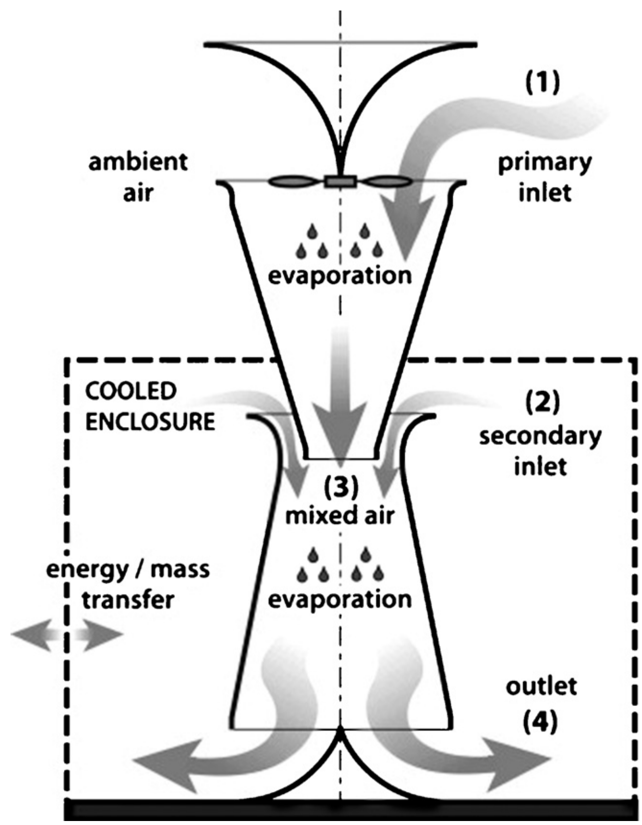

Fig. 22. Schematic design of multi stage down draft windcatcher [36,58].

4. Windcatcher configuration

Configuration of the different components of a windcatchers is one of the important parameter determining the efficiency of that particular windcatcher. Inclination angle and meteorological parameter and louver configuration are some examples of these configurations which are going to be discussed in this section.

4.1. Inclination angle and meteorological parameters

The relationship of meteorological factors and ventilation has always been the focus of various researchers. Geometry and inclination angle is the main rubrics of this realm of study. For instance, Chen from Australia in collaboration with some other scholars from Denmark and Hong Kong carried out a study on solar chimney inclinations to determine the optimum inclination [70].

The result showed that the most efficient inclination angle for a 1.5 m high device is around 45° [70]. Likewise, Mozafari and his colleagues conducted a CFD simulation as well as an experimental wind tunnel utilizing smoke visualization test to examine the inclination of windcatcher and its efficiency [29].

For that a windcatcher model was examined to measure the induced volumetric airflow and the pressure coefficients. The orientation of the constructed model was changed in wind tunnel

Fig. 23. the multi stage windcatcher prototype [36,58].

and CFD simulation and the volumetric airflow, and the pressure coefficients were measured. The study found out that the efficiency of windcatchers is related to the pressure coefficients of its opening and air incident angle [71].

Measuring these pressure coefficients revealed a new phenomenon known as short-circuiting. This phenomenon occurs on multi opening windcatchers once wind enters from one side and exhausts from the other side without circulation [71]. The study affirmed that the worst inclination angle for having the highest rate of short-circuiting is 60° whereas the most efficient angle for having the highest ventilation rate is 90° [71] (see Fig. 24).

4.2. Louver configuration in commercial windcatcher

A louver in a windcatcher induces external wind into the building and safeguards the building from penetration of the rainwater. The louver is considered functional once the flow separation happens over the top surface of the louver airfoil. Based on aerodynamic theory when the angle of the airfoil of a louver namely attack angle, reaches to a certain point flow separation occurs [72].

The parameters that are determinant in efficiency of louvers are its geometry, louver angle, surface roughness, the void between two louvers, and the sharpness of the edges as well as Reynolds number [73]. Reynolds number is a dimensionless number that gives a measure of inertial force and for the realm of the study of building is calculated as follows: $Re = UL/v$, U = wind speed, L = length scale of louver and v = kinematic viscosity of air [74].

There has always been a question that how much the windcatcher louver quality contributes the performance of windcatcher. For answering this question, Hughs and his colleague from Sheffield Hallam University in the UK explored the efficiency of the wind vent, a kind of commercial windcatcher, and the external angle of louver.

Despite the fact that a normal windcatcher louver has a 45° angled louver, no one had conducted any research on suitability of these louvers (see Fig. 25). Therefore, the research team made eight CFD models using FLUENT version, including various windcatchers altered in 5° increments for a range of 10–45° louver [73]. They consecutively measured the air velocity and pressure to investigate the optimum angle of the louvers.

The result showed that a louver angle of 35° has the maximum efficiency [73]. Moreover, in terms of comfort level of occupants, a 35° windcatcher louver produces 45% more comfort in comparison of louver with angle of 45°, and the former one reduces 42% trailing-edge stall pressure produced.

Meanwhile, another group of scholars at Hong Kong Poly Technique University focused on louver effects. They employed k–ε model and RNG k–ε model, wind tunnel and eventually CFD simulation to investigate the effects of the number of layers and the length of the louvers and its relevancy to windcatcher efficiency [7]. For the said purpose, a square cross-section windcatcher was mounted

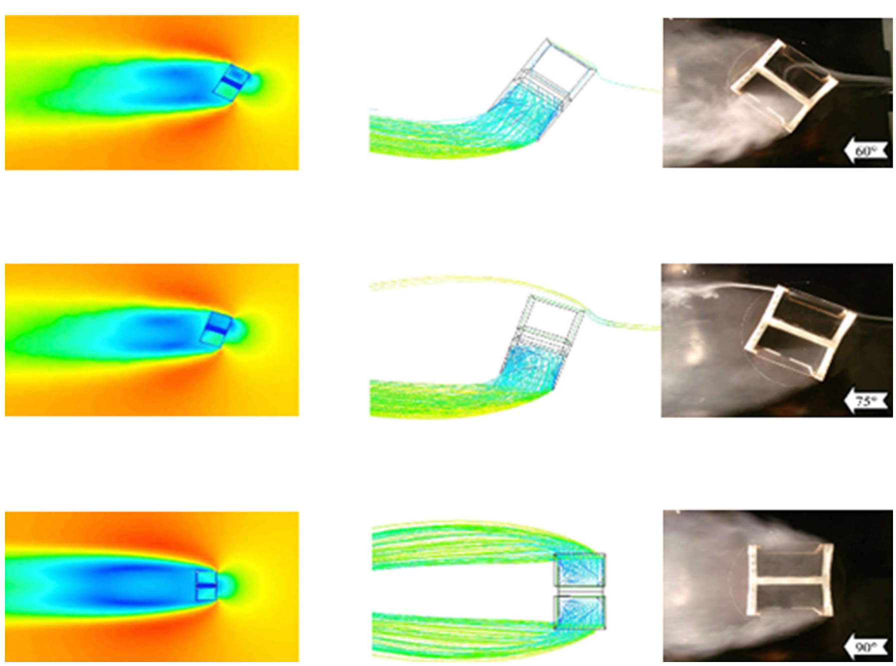

Fig. 24. Efficiency and incantation angle [71].

Fig. 25. Standard 45° louver [73].

on a typical room. For having a fair comparison the researchers used the dimensions of the windcatcher and the room of the Hughs study [73], nevertheless the length and number of layers were altered [7].

In order to make the experiment feasible, the external wind velocity and wind incidence angle were hypothesized 3 m/s, and ($\alpha = 0°$) respectively [7]. Moreover, to avoid any bias cause of change of louver angle, as a significant parameter in efficiency of windcatcher, the uniform louver external angle (45 °C) was employed. For studying the effects of layers of louvers, seven various models with the same louver length and external angle, namely louver 2, 3, 4, 6, 8, 10, 12, were analyzed.

In spite of that various models had diverse layers; the height and gap of two adjacent layers were considered exactly the same. A length ratio l¼ L/Lref to evaluate the effect of the louver length was also applied where L is the nominal length of louver, while Lref is the louver length when the dimension of louver projection equates L gap. The length ratios of 0.5, 1, 2, 3, 4, 5, 6, were simulated using CFD modeling in their study.

The study revealed that increasing the number of louver layers contributes to more efficiency (see Fig. 26). For instance, the airflow rates of three layers were shown 12.7% more than two louver layers [7]. In spite of that adding louver layers, increases the air flow rate, the study result ascertained that surpassing 6 louver layers, the increase of the airflow would be less than 1.5% [7].

Increase of the airflow rate which leads to higher pressure resistance; prevent the wind to enter the windcatcher with six louvers and above. Moreover, the existence of a short circuit at the top layers of the windcatchers prevents the wind to enter the windcatcher with six louvers and above either [7]. This phenomenon could be easily observed in the airflow pattern in, and around the windcatcher with 12 layers, where the wind enters the 12-layer louvers through the lower louvers and exit from other louvers [7].

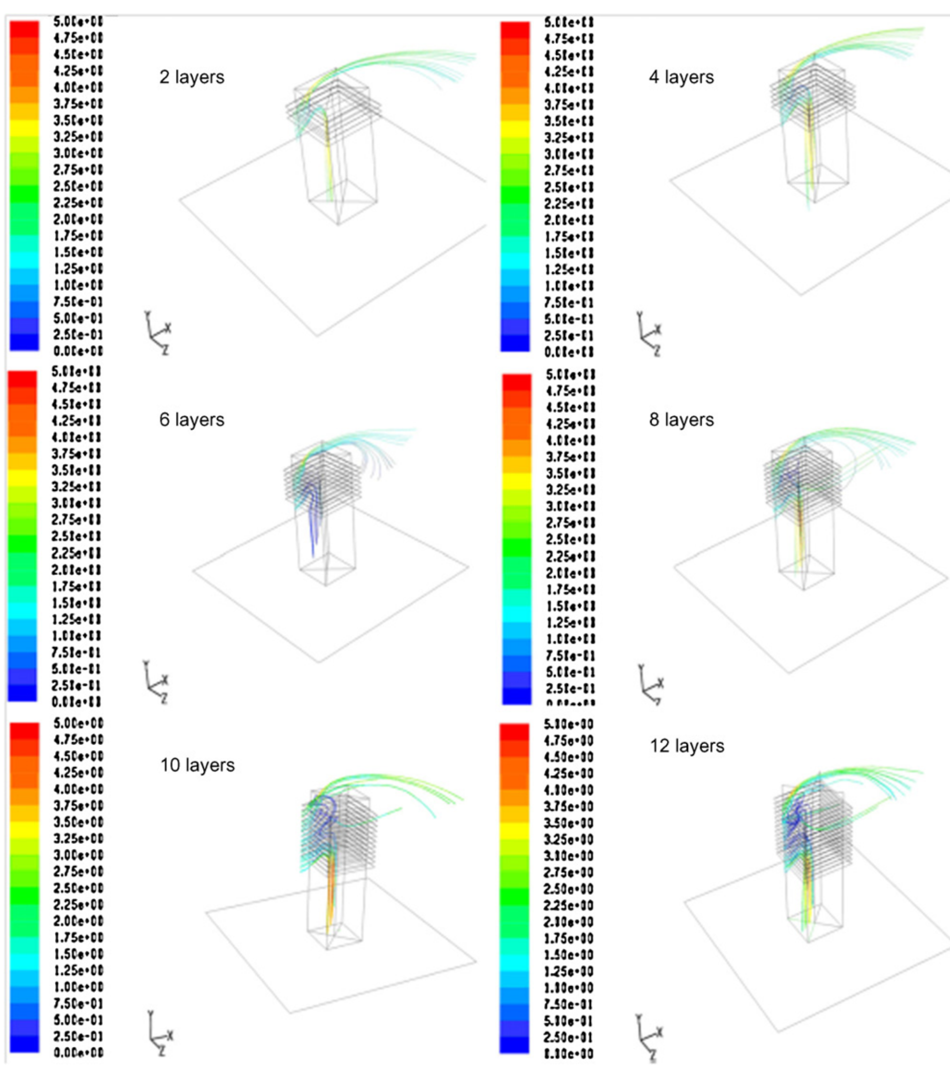

Fig. 26. The efficiency of windcatcher and number of louver layers [7].

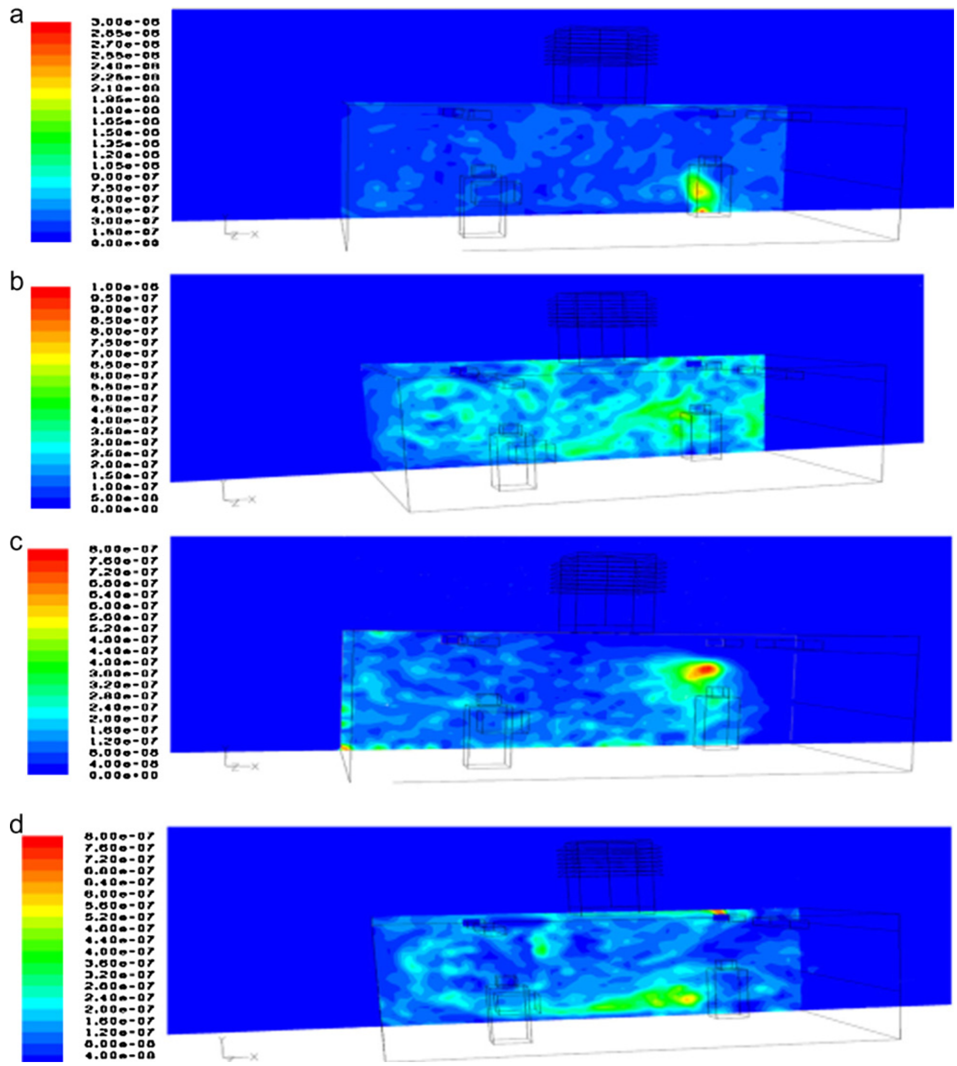

Fig. 27. Contaminant concentration modeling in Cases 1–4 [7].

The study also revealed that when L = Lref the highest air flow rate passes through the windcatcher [7]. Moreover, if the dimension of louver projection is equivalent as the dimension of the gap of two adjacent louvers, the windcatcher will work more efficiently [7]. However, the airflow rate goes down and the efficiency of windcatcher is reduced once the length coefficient become double the Lref [7].

4.3. Windows configuration

An engineering positioning of windows is proposed as the potential remedy to cool the buildings in dense urban environments. Engineering designed windows are used in the building envelope not only to draw wind but also to expel the air [75]. For investigating the effects of windows positioning in relation to windcatcher efficiency such as buoyancy, a group of scholars in Hong Kong conducted a study by selecting four cases with different ventilation strategies in a full-scale office [7].

They aimed to investigate the effects of buoyancy and window position, leeward sides and windward side, on the thermal conditions of the office. Heat sources in a format of two computers, four lights and four persons, were provided to foster the stack effect (see Table 4).

They set four combination forms with following specifications: Case 1: No buoyancy and no windows; Case 2: With buoyancy effect but no windows; Case 3: with buoyancy effect and windows are installed in wind ward; and Case 4: with buoyancy effect and windows are installed at lee ward side.

Table 4
Heat sources details [7].

Heat source	Dimension (m)	Heat input (W)
First person	0.4 × 0.35 × 1.1	75
Second person	0.4 × 0.35 × 1.1	75
First computer	0.35 × 0.34 × 0.4	173
Second computer	0.35 × 0.34 × 0.4	108
Bulb1	0.2 × 0.15 × 1.2	34
Bulb 2	0.2 × 0.15 × 1.2	34
Bulb 3	0.2 × 0.15 × 1.2	34
Bulb 4	0.2 × 0.15 × 1.2	34

Meanwhile, an 80 cm × 80 cm × 150 cm windcatcher with 6 layers of louvers is installed at the center of the office roof. The result upheld that when the window is positioned on the windward side, there is a significant positive difference in airflow pattern comparing to other cases (see Fig. 27).

In contrast, positioning the windows in windward amplify the short circuit phenomenon, since the wind enters the building through the windward windows and immediately leaves the room from the windcatcher which functions only as an out let [7]. Therefore, the worse configuration between Cases 3 and 4 which is not

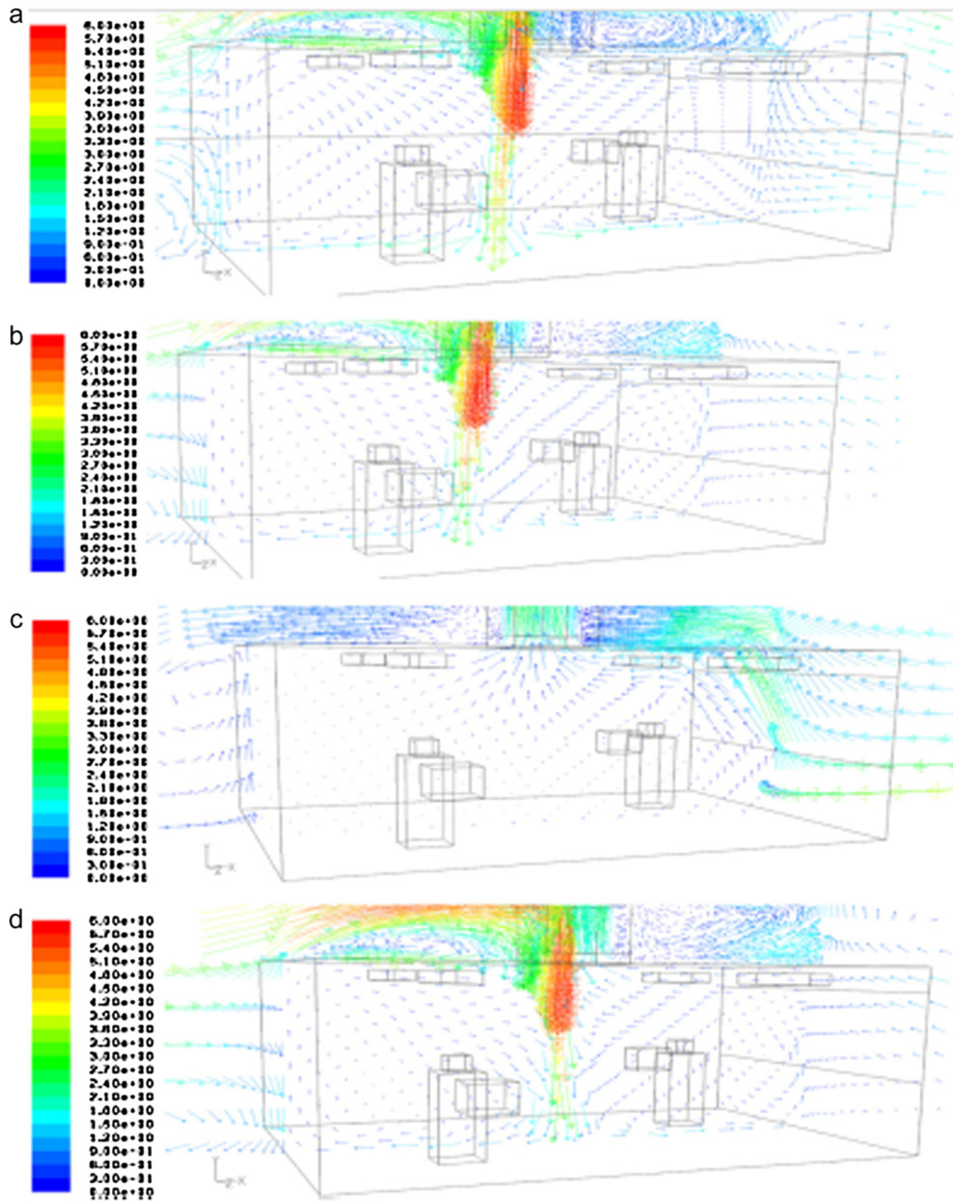

Fig. 28. Airflow pattern (a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4 [7].

Table 5
Airflow rate for various configurations.

Case number	Air flow rate (m^3/h)
1	1560
2	1565
3	5570
4	2310

propitious for ventilation is to position windows in the windward side in an integrated windcatcher and windows building. However, the best configuration in a above building is appeared to be leeward side windows (Case 4), in which negative pressure generated on the lee ward side causes induction of extra wind into the room from the outside (see Table 5).

Referring to Table 5, the study represent that Cases 1 and 2 performs almost the same and have the equal airflow rate since the effect of buoyancy, not to say is negligible, is much lower in comparison to wind effect and the airflow rate of Case 4 is almost 1.5 time more than both Cases 1 and 2 [44].

This study also investigated the particle diffusion and contaminant dispersion in the simulated building. Using particle as big as d_p = ¼ 1 μm, 2.5 μm, 5 μm and 10 μm showed that the particle concentration (kg/m^3) in the center position between the human simulator and computer for Case 1 is more than Case 2 [7]. The study also revealed that the windcatcher managed to reduce contaminant concentration of the central region drastically [7].

Investigating Case 3 showed that when the window is positioned on the windward side, less contaminant concentration is found in Case 3 compared to Case 1 and the air of windows area are almost as clean as outside (see Fig. 28). Case 4 shows that having an integrated windcatcher with leeward positioned windows contributes a lot in removing the contamination and therefore, performs the best [7].

4.4. Combination of windcatcher and solar chimney

Solar applications are attracting many people to use for their advantages such as their economic benefits, low maintenance and long life span in one hand and their system's modularity, low noise

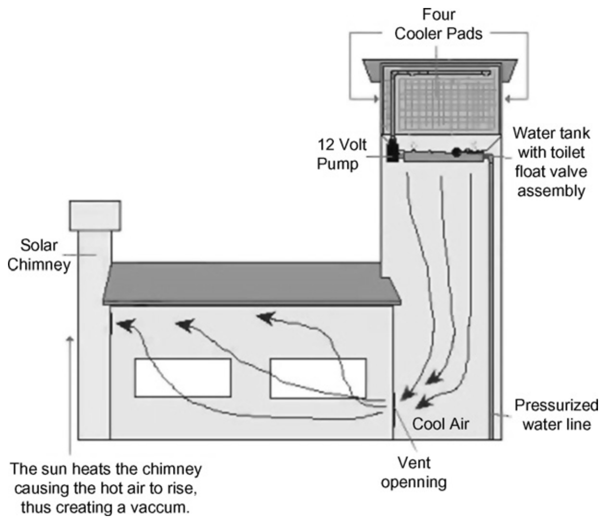

Fig. 29. A combined windcatcher and solar chimney [43].

level in another hand [76]. Solar chimney is also not exempted from those benefits. Solar chimney or thermal chimney is a ventilation method and a thermo-siphoning air channel that uses convection of air heated by solar energy through thermal buoyancy [77,78]. In simple words, this channel uses solar radiation to enhance the temperature leads to density drop and rise of air within the solar chimney and eventually to expel the air outside [78].

The parameters that are involved the performance of a solar chimney are solar absorptance, solar chimney height, and solar transmittance and air gap width [78]. It is argued that the best roof for integrating solar chimney is a gable roof which can be designed to form the roof solar collectors [77]. Studies on windcatcher combined with the solar chimney which has been carried out by various researchers indicates that the combination of solar chimney and windcatcher works more efficiently since it increases the mass flow rate [43,58].

The use of solar chimney in combination with windcatcher might be the solution when there is not a suitable wind [28,79]. For testing this hypothesis Kalantar conducted a simulation study and experimental measurement on the combination of a windcatcher and solar chimney to examine the efficiency (see Fig. 29).

The result of this study revealed that this solar chimney combined with the windcatcher cooling system can alter the air temperature up to 15 °C cooler [43]. The study also affirmed that under the wind velocity of 3 m/s, a 10 m windcatcher with a cross-sectional area of 2 m^2 could produce a peak cooling output of more than 100 kW, whilst it consumes only 0.025 kg/s water [43]. The said system can easily do the air-conditioning of 700 m^2 building in an arid area [43].

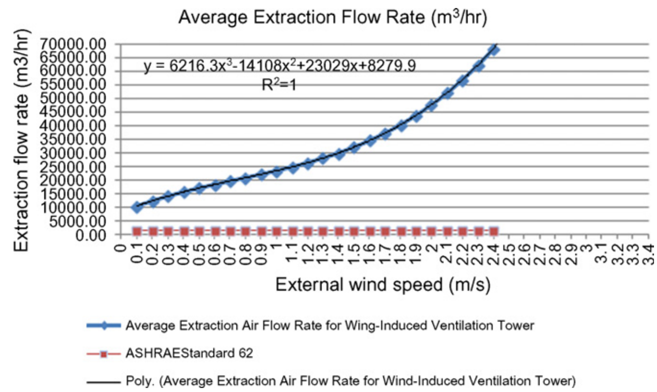

Fig. 30. Average extraction air flow rate based on external wind speed [80].

There are also another study, which emphasizes on the efficiency of integrated solar chimney and windcatcher. Based on the study conducted in Indian Institute of Technology, it was found out that for an ambient wind of 1.0 m/s, an individual windcatcher produces a mass flow rate of 0.75 kg/s, nonetheless, the integrated solar chimney and windcatcher produce approximately a double air flow of the former one amounting to 1.4 kg/s at 700 W/m^2 [79]. The study also revealed that a combined solar chimney and windcatcher operate more efficiently in lower wind speeds than higher wind speed [79].

4.5. Combination of windcatcher and inverted airfoil

The authors of this paper conducted an empirical research of a windcatcher under hot and humid climatic conditions. Based on empirical data, at external wind speed of 2 m/s, the wind tower is able to generate average extraction air flow rate of 47,634.6 m^3/h [80] (see Fig. 30).

The roof profile of the windcatcher is designed based on an inverted airplane wing shaped roof which uses Bernoulli's effect to induce low pressure at the top of the wind tower (see Fig. 31).

This experimental research revealed the potential of windcatcher capability under hot and humid climatic conditions to generate sufficient air flow rate for indoor thermal comfort for its occupants.

5. Summary

Although incorporation of windcatcher in modern building industry has been neglected, windcatcher is still considered as one

Fig. 31. Experimental house with an inverted airplane wing windcatcher [80].

of the most important passive techniques. Windcatchers can be categorized into three groups of vernacular windcatchers, modern windcatcher and eventually super modern windcatchers.

There are two main driving forces behind the mechanism of windcatcher, namely buoyancy effect and external wind, where the latter is the main contributor of windcatcher operation. Buoyancy effect is a physical phenomenon that is promoted due to the existence of internal and external different temperature. Number of opening in a windcatchers affects its efficiency in a way that as much as the number of opening increases its efficiency decreases. However, in places that there is no prevailing wind the best option is multi opening windcatchers.

Form of the windcatcher is also another attributes contributing to its efficiency where performances of octagonal windcatchers are weaker than square and rectangular cross-section ones. Inclination angle of a windcatcher orientation in relationship to the prevailing wind is another important parameter of efficiency where the 60° inclination angle for having the highest rate of short-circuiting is the worst inclination whereas the most efficient angle for having the highest ventilation rate is 90°.

Louver configuration is another rubric that alters the efficiency of a windcatcher, i.e. as much as the layer of louvers increases more efficiency would be achieved. Likewise, the optimum, louver angel is proposed 35° for the places which have a prevailing wind direction. The optimum location for positioning windows is also suggested the leeward side. Positioning a window in a building equipped with a windcatcher not only foster the ventilation rate but also reduce contaminant concentration inside a building.

Dampers and egg crate grilles generally reduce the efficiency up to 71%, depending to the speed of wind. However, they assist the movement of large air flow rate to replenish of fresh air. Installation a heat source inside the windcatcher facilitates the movement of air flow due to buoyancy effect and increases the air movement up to 1.5 times. Preventing the air from leaving from other openings as well as preventing dust and birds from entering the inlet of the wind tower can be achieved by using a dampers and egg crate grills either.

Evaporative cooling technique, either direct or in-direct, is one of the various techniques, which is utilized in windcatcher and can alter the temperature 10° cooler in the arid areas. However, its applicability for extreme hot and humid climate is a matter of a question. Use of the underground water canal known as Qanat and water pond in traditional architecture and spry of water and utilizing new material, that can maintain wet surface in modern architecture are some of the examples of this technique.

Down draft windcatcher is an innovative type of windcatcher, which utilizes the evaporative cooling phenomenon for vast or semi enclosed areas such as courtyards, particularly in arid regions and operates based on three following principals: (1) there is a positive wind pressure at the entrance of the windcatcher or inlet; (2) the spray of the water at the top of windcatcher causes the air to descend since it became denser; and (3) there is a momentum transferred from the sprayed water to move the air downward. This kind of windcatcher is unique which can operate even in the absence of wind due to the buoyancy effect created by evaporative cooling and is highly efficient in terms of conserving water. The maximum efficiency of this system is achieved if a fine spray is being employed.

The idea of using the windcatcher for semi-closed and outdoor environment has been practiced by some researchers in various countries such as Spain. However, it has not shown the same efficiency of indoor. Despite its low efficiency, if evaporative cooling is being incorporated and considering its shading efficiency, it can still be considered an option which can reduce the temperature by 3–4 °C for semi-enclosed zones.

Hybrid windcatchers are the one which are working in combination of mechanical cooling and ventilation systems. This initiative is very useful and innovative, which conserves a lot of energy but requires a very high-tech electrical controlling system to operate. The combination of different passive tools such as solar chimney and windcatcher is also recommended for its efficiency where a combined solar chimney and windcatcher can serve to reduce the temperature up to 15° and double the internal air flow. A combination of inverted air foil and a windcatcher is suggested for tropical climate for its efficiency in improving the internal air movement and thermal comfort.

6. Recommendation for further studies

Studying on the height, various materials, employment of dehumidification and evaporative cooling for humid climates, aerodynamic of windcatchers, use of phase change material, structure and color of windcatcher are among the engineering topics, which is required to be covered in future studies. Moreover, cost and benefit study of windcatchers in newly built and existing renovation buildings, feasibility study of introducing windcatchers to existing governmental and private buildings, analyzing the cost of incorporating hybrid windcatcher and the revenue which can be gained as a result of its energy saving for a specific period of time are among the economic subjects which should be studied thoroughly in the future researches. Finally, the public attitude and their preference towards this passive technology for different countries should be gauged in social science.

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